# Calculations executed for the 3-bladed rotor of the VIRYA-5B3 windmill ($\lambda_d = 6$) meant for connection to the axial flux generator of Hefei Top Grand type TGET450-5KW-300R for grid connection

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# 1 Introduction

The original VIRYA-5 windmill has a 2-bladed rotor with a design tip speed ratio $\lambda_d = 7$ and wooden blades which are connected to each other by means of a twisted steel strip. The rotor is driving a 34-pole PM-generator made from the housing of an asynchronous motor. The windmill is meant to be coupled directly to the 3-phase asynchronous motor of a centrifugal pump. This VIRYA-5 windmill is described in report KD 614 (ref. 1).

Manufacture of a 34-pole PM-generator is a lot of work and requires special machines and skills. A high pole number is only required for direct connection to a pump motor. There might be a market in The Netherlands for a grid connected windmill with a rotor diameter of 5 m as in the future, pumping of natural gas must be stopped. In this case most of the energy supplied by the windmill can be used to generate heat, using a heat pump. But this requires a windmill which is connected to the grid by an inverter. This option is described in chapter 2.4 of the Dutch report KD 709 (ref. 2) for the VIRYA-6.5 windmill. In chapter 5 of KD 709 it has been investigated if the original 46-pole radial flux PM-generator of the VIRYA-6.5 can be replaced by a very big axial flux generator of Hefei Top Grand type TGET but this isn’t possible.

So it was investigated a smaller generator of Hefei Top Grand with type number TGET450-5kW-300R could be used in combination with the VIRYA-5. It appeared that the rotational speed of the VIRYA-5 is a bit too high caused by the rather high design tip speed ratio $\lambda_d = 7$. It is also expected that a 2-bladed rotor isn’t found beautiful enough for use in The Netherlands, so a new 3-bladed rotor with a design tip speed ratio $\lambda_d = 6$ is designed. To distinguish this windmill from the original 2-bladed VIRYA-5, it is called the VIRYA-5B3. The advantage of the lower design tip speed ratio is also that the noise production will be lower. An extra advantage of a 3-blade rotor is that the gyroscopic moment in the rotor shaft isn’t fluctuating and this prevents vibrations.

The axial flux generators of Hefei Top Grand type TGET have an outer rotor, so the whole generator housing is rotating. The generator has a 3-phase winding which is connected in star internally. So only the three phase wires are coming out of the hollow generator shaft. For use in combination with an inverter, the 3-phase current has to be rectified. Rectification of the winding is described in report KD 340 (ref. 3). Selection of the right inverter is out of the scope of this report.

The windmill is provided with the so called hinged side vane safety system which is described in report KD 213 (ref. 4) for the VIRYA-4.2. The VIRYA-5B3 makes use of the same head as the VIRYA-5 which has a 12 mm thick vane blade made out of water proof ply wood size 1.22 * 1.22 m, so half a standard sheet of 1.22 * 2.44 m. The head is derived from the head of the VIRYA-4.2 and the VIRYA-4.6B2 by lengthening of the thinnest vane arm pipe. The VIRYA-5B3 also has a vane blade size 1.22 * 1.22 m with a thickness of 12 mm but heavier meranti ply wood is used in stead of the lighter okoume ply wood resulting in a rated wind speed of about 11 m/s. The head geometry is checked in chapter 10 of KD 614. A top view of the head is given in figure 10 of KD 614. The generator bracket has to be modified if an axial flux generator of Hefei Top Grand is used.

The VIRYA-5B3 can make use the same 12 m lattice tower which is also used for the VIRYA-4.2 and the VIRYA-4.6B2. However, manufacture of such a tower is a lot of work. It might be possible to design a new 12 m, 15 m or 18 m high free standing tower made out of four, five or six, 3 m long pipes with different diameters. Development of such a new tubular tower is out of the scope of this report.

## 2 Description of the rotor of the VIRYA-5B3 windmill

The 3-bladed rotor of the VIRYA-5B3 windmill has a diameter D = 5 m and a design tip speed ratio $\lambda_d = 6$. The rotor has blades with a constant chord and no twist and is provided with a Gö 623 or a Gö 711-12% airfoil. A blade is made out of a wooden plank with dimensions of 28.8 * 240 * 2270 mm. The airfoil is made over the whole length of the blade. The blade has no twist so the blade angle $\beta$ is the same for the whole blade.

The blades are connected to each other by a hub plate made out of 8 mm stainless steel sheet. The hub plate has three 200 mm wide and 450 mm long ears which are twisted such that the correct blade angle is realised. The six outside and three inside corners are rounded with r = 30 mm. Ten hub plates can be laser cut from a standard sheet size 1.5 * 3 m. The overlap in between a blade and an ear is 220 mm which results in a free blade length of 2.05 m. Each blade is connected to the strip by three M12 bolts. A 3 mm thick curved stainless steel strip size 60 * 220 mm is placed under the bolt heads to prevent deformation of the wood when the bolts are tightened.

The hub plate is bolted to the generator housing by means of ten bolts M12. The rotor is balanced by adding balance weights under the connecting bolts. A sketch of the VIRYA-5B3 rotor is given in figure 1.

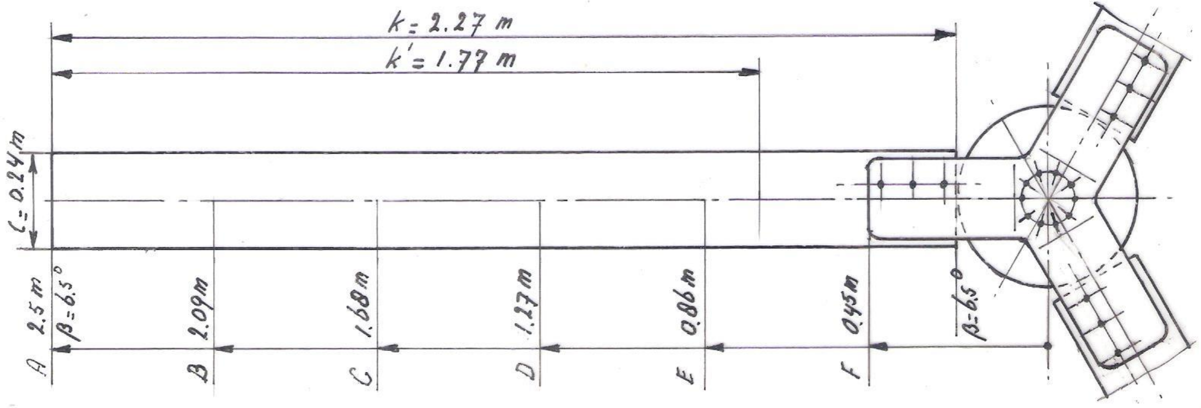

fig. 1 Sketch VIRYA-5B3 rotor

## 3 Calculation of the rotor geometry

The rotor geometry is determined using the method and the formulas as given in report KD 35 (ref. 5). This report (KD 710) has its own formula numbering. Substitution of $\lambda_d = 6$ and R = 2.5 m in formula (5.1) of KD 35 gives:

$$\lambda_{r\,d} = 2.4 * r \qquad (-) \qquad (1)$$

Formula's (5.2) and (5.3) of KD 35 stay the same so:

$$\beta = \phi - \alpha \qquad (°) \qquad (2)$$

$$\phi = 2/3 \arctan 1 / \lambda_{r\,d} \qquad (°) \qquad (3)$$

Substitution of B = 3 and c = 0.24 m in formula (5.4) of KD 35 gives:

$$C_l = 34.907\ r\ (1 - \cos\phi) \qquad (-) \qquad (4)$$

Substitution of V = 5 m/s and c = 0.24 m in formula (5.5) of KD 35 gives:

$$R_{e\,r} = 0.8 * 10^5 * \sqrt{(\lambda_{r\,d}^2 + 4/9)} \qquad (-) \qquad (5)$$

The blade is calculated for six stations A till F which have a distance of 0.41 m of one to another. Cross section F corresponds to the end of the ear of the hub plate. The blade has a constant chord and the calculations therefore correspond with the example as given in chapter 5.4.2 of KD 35. This means that the blade is designed with a low lift coefficient at the tip and with a high lift coefficient at the root.

First the theoretical values are determined for $C_l$, $\alpha$ and $\beta$ and next $\beta$ is linearised such that the twist is constant and that the linearised values for the outer part of the blade correspond as good as possible with the theoretical values. The result of the calculations is given in table 1.

The aerodynamic characteristics of the Gö 623 airfoil are given in report KD 35 (ref. 5) and in report KD 463 (ref. 6). As an alternative, it seems possible to use the Gö 711-12% airfoil. This airfoil is described in report KD 333 (ref. 7). This airfoil is flat over 97.5 % of the chord and is therefore easier to manufacture. The Reynolds values for the stations are calculated for a wind speed of 5 m/s because this is a reasonable wind speed for a windmill which is used in areas with moderate wind speeds.

| station | r (m) | $\lambda_{rd}$ (-) | $\phi$ (°) | c (m) | $C_{l\,th}$ (-) | $C_{l\,lin}$ (-) | $R_{e\,r} * 10^{-5}$ V = 5 m/s | $R_e * 10^{-5}$ Gö 623 | $\alpha_{th}$ (°) | $\alpha_{lin}$ (°) | $\beta_{th}$ (°) | $\beta_{lin}$ (°) | $C_d/C_{l\,lin}$ (-) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 2.5 | 6 | 6.3 | 0.24 | 0.53 | 0.51 | 4.83 | 4.2 | 0.0 | -0.2 | 6.3 | 6.5 | 0.022 |
| B | 2.09 | 5.016 | 7.5 | 0.24 | 0.63 | 0.63 | 4.05 | 4.2 | 1.0 | 1.0 | 6.5 | 6.5 | 0.021 |
| C | 1.68 | 4.032 | 9.3 | 0.24 | 0.77 | 0.79 | 3.27 | 4.2 | 2.6 | 2.8 | 6.7 | 6.5 | 0.022 |
| D | 1.27 | 3.048 | 12.1 | 0.24 | 0.99 | 0.99 | 2.50 | 2.3 | 5.6 | 5.6 | 6.5 | 6.5 | 0.026 |
| E | 0.86 | 2.064 | 17.2 | 0.24 | 1.35 | 1.23 | 1.74 | 1.2 | - | 10.7 | - | 6.5 | 0.052 |
| F | 0.45 | 0.928 | 31.4 | 0.24 | 2.30 | - | 0.91 | 1.2 | - | 24.9 | - | 6.5 | - |

table 1 Calculation of the blade geometry of the VIRYA-5B3 rotor

No value for $\alpha_{th}$ and therefore for $\beta_{th}$ is found for stations E and F because the required $C_l$ values can't be generated. The variation of the theoretical blade angle $\beta_{th}$ is only little for the most important outer stations A up to D and varies in between 6.3° and 6.7°. Therefore it is allowed to take a constant value of $\beta_{lin}$ = 6.5° for the whole blade. The ears of the hub plate are twisted 6.5° right hand in between the generator hub and the blade root.

## 4 Determination of the $C_p$-$\lambda$ and the $C_q$-$\lambda$ curves

The determination of the $C_p$-$\lambda$ and $C_q$-$\lambda$ curves is given in chapter 6 of KD 35. The average $C_d/C_l$ ratio for the most important outer part of the blade is about 0.023. Figure 4.7 of KD 35 (for B = 3) and $\lambda_{opt} = 6$ and $C_d/C_l = 0.023$ gives $C_{p\,th} = 0.47$ (interpolation in between the lines for $C_d/C_l = 0.02$ and $C_d/C_l = 0.03$).

The blade is stalling at station F. For the calculation of the maximum $C_p$ therefore not the whole blade length k = 2.27 m is taken into account but only the part up to 0.28 m outside station F. This gives an effective blade length k' = 1.77 m.

Substitution of $C_{p\,th} = 0.47$, R = 2.5 m and effective blade length k' = 1.77 m in formula 6.3 of KD 35 gives $C_{p\,max} = 0.43$. $C_{q\,opt} = C_{p\,max} / \lambda_{opt} = 0.43 / 6 = 0.0717$. Substitution of $\lambda_{opt} = \lambda_d = 6$ in formula 6.4 of KD 35 gives $\lambda_{unl} = 9.6$. The starting torque coefficient is calculated with formula 6.12 of KD 35 which is given by:

$$C_{q\,start} = 0.75 * B * (R - ½k) * C_l * c * k / \pi R^3 \qquad (-) \qquad (6)$$

The blade angle is 6.5° for the whole blade. For a non rotating rotor, the angle of attack $\alpha$ is therefore 90° - 6.5° = 83.5°.

The aerodynamic characteristics for the Gö 623 aren't given for large angles of $\alpha$ in KD 463. However, the estimated $C_l$-$\alpha$ curve for large values of $\alpha$ is given as figure 5.10 of KD 35 (ref. 5). For $\alpha = 83.5°$ it can be read that $C_l = 0.23$. The whole blade is stalling during starting and therefore now the whole blade length k = 2.27 m is taken.

Substitution of B = 3, R = 2.5 m, k = 2.27 m, $C_l = 0.23$ and c = 0.24 m in formula 6 gives that $C_{q\ start} = 0.0078$. For the ratio between the starting torque and the optimum torque we find that it is 0.0078 / 0.0717 = 0.109. This is acceptable for a rotor with $\lambda_d = 6$.

The starting wind speed $V_{start}$ of the rotor is calculated with formula 8.6 of KD 35 which is given by:

$$V_{start} = \sqrt{\left(\frac{Q_s}{C_{q\ start} * \frac{1}{2}\rho * \pi R^3}\right)} \quad \text{(m/s)} \qquad (7)$$

At point 11 of the specification of the generator it is mentioned that the starting torque is smaller than 0.3 Nm. This is very low and I doubt if this is correct if the generator has a seal on the shaft. The generator can be used without a seal for a vertical axis wind turbine but for a horizontal axis wind turbine, a seal is certainly necessary to prevent that water enters the bearings. Assume that the sticking torque with a seal is 2 Nm.

If the generator has no seal on the shaft and no outside chamber for mounting of an oil seal, it might be possible to use a V-ring of manufacture Forsheda type V-60A. This ring is clamped around the shaft and has an elastic lip which is pressed against the collar at the shaft side. But this is only possible if the collar surface is machined flat with a low roughness and if the lip isn't running over the threaded holes. Some grease has to be put on the lip at mounting.

Substitution of $Q_s = 2$ Nm, $C_{q\ start} = 0.0078$, $\rho = 1.2$ kg/m$^3$ and R = 2.5 m in formula 7 gives that $V_{start} = 3$ m/s. This is acceptable low for a 3-bladed rotor with a design tip speed ratio $\lambda_d = 6$ and a rated wind speed $V_{rated} = 11$ m/s.

In chapter 6.4 of KD 35 it is explained how rather accurate $C_p$-$\lambda$ and $C_q$-$\lambda$ curves can be determined if only two points of the $C_p$-$\lambda$ curve and one point of the $C_q$-$\lambda$ curve are known. The first part of the $C_q$-$\lambda$ curve is determined according to KD 35 by drawing an S-shaped line which is horizontal for $\lambda = 0$. Kragten Design developed a method with which the value of $C_q$ for low values of $\lambda$ can be determined (see report KD 97 ref. 8). With this method, it can be determined that the $C_q$-$\lambda$ curve is about straight and horizontal for low values of $\lambda$ if a Gö 623 airfoil is used. A scale model of a three bladed rotor with constant chord and blade angle and with a design tip speed ratio $\lambda_d = 6$ has been measured in the wind tunnel already on 20-11-1980. It has been found that the maximum $C_p$ was more than 0.4 and that the $C_q$-$\lambda$ curve for low values of $\lambda$ was not horizontal but somewhat rising. This effect has been taken into account and the estimated $C_p$-$\lambda$ and $C_q$-$\lambda$ curves for the VIRYA-5B3 rotor are given in figure 2 and 3.

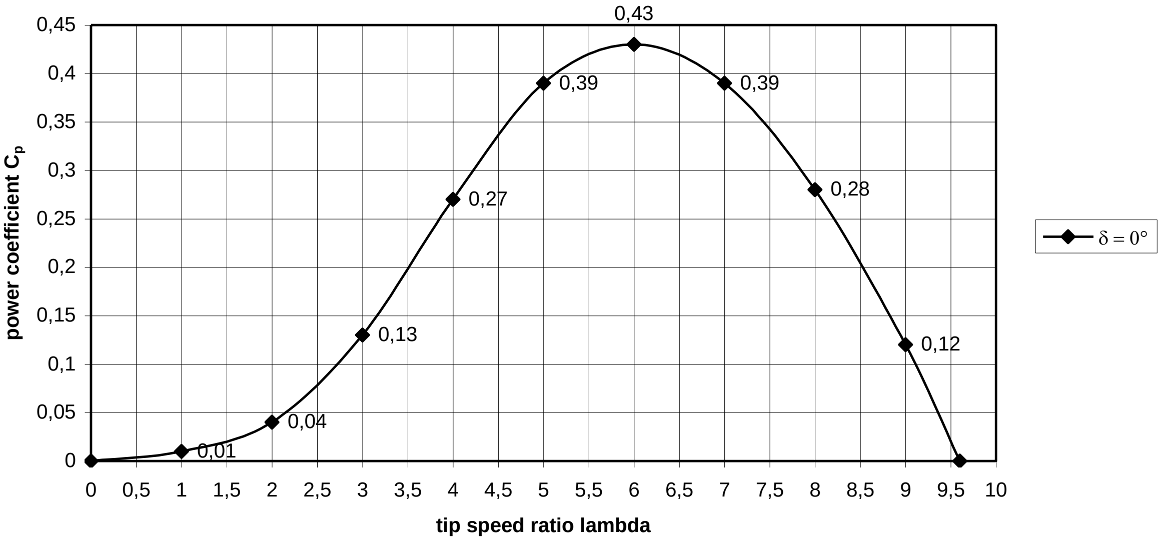

fig. 2 Estimated $C_p$-λ curve for the VIRYA-5B3 rotor for the wind direction perpendicular to the rotor (δ = 0°)

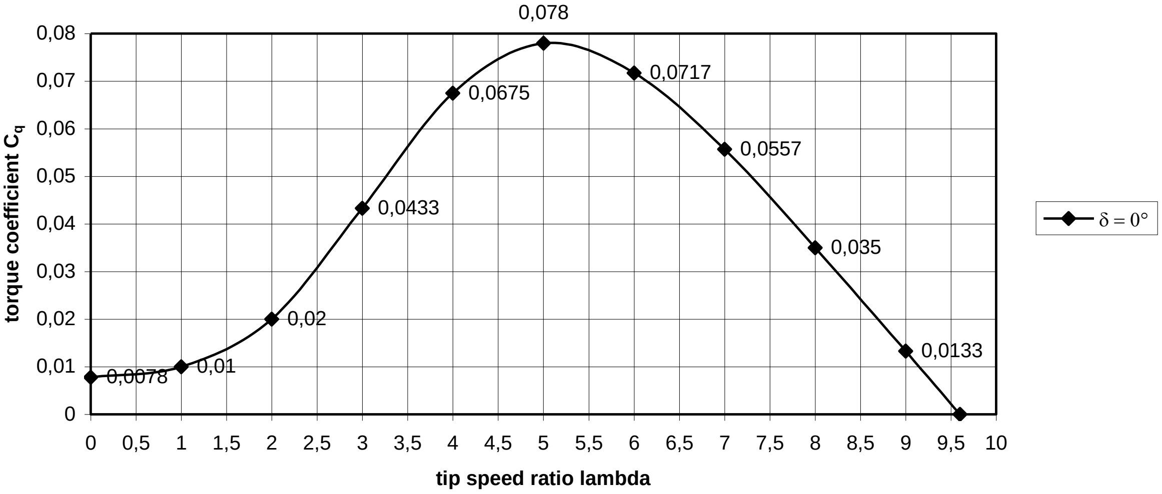

fig. 3 Estimated $C_q$-λ curve for the VIRYA-5B3 rotor for the wind direction perpendicular to the rotor (δ = 0°)

## 5 Determination of the P-n curves and the optimum cubic line

The determination of the P-n curves of a windmill rotor is described in chapter 8 of KD 35. One needs a $C_p$-λ curve of the rotor and a δ-V curve of the safety system together with the formulas for the power P and the rotational speed n. The $C_p$-λ curve is given in figure 2.

The δ-V curve of the safety system depends on the vane blade weight per area. In report KD 213 (ref. 4), a method is given to check the estimated δ-V curve and the estimated δ-V curve of the VIRYA-4.2 windmill is checked as an example. The vane blade of the VIRYA-4.2 is made of 9 mm meranti plywood. This vane blade gives a rated wind speed $V_{rated}$ of about 9.5 m/s. The vane blade can’t be made too thin otherwise it will flutter at high wind speeds. So it is estimated that the bigger vane blade of the VIRYA-5B3 needs a thickness of 12 mm. If the meranti plywood is used, this results in increase of the weight per area with a factor 12 / 9 = 1.333. The aerodynamic force on the vane blade increases by $V^2$.

The rated wind speed will therefore increase by a factor √ 1.333 = 1.155. So it becomes 1.155 * 9.5 = 11 m/s. The estimated δ-V curve for $V_{rated}$ = 11 m/s is given in figure 4.

The head starts to turn away at a wind speed of about 7 m/s. For wind speeds above 11 m/s it is supposed that the head turns out of the wind such that the component of the wind speed perpendicular to the rotor plane, is staying constant. The P-n curve for 11 m/s will therefore also be valid for wind speeds higher than 11 m/s.

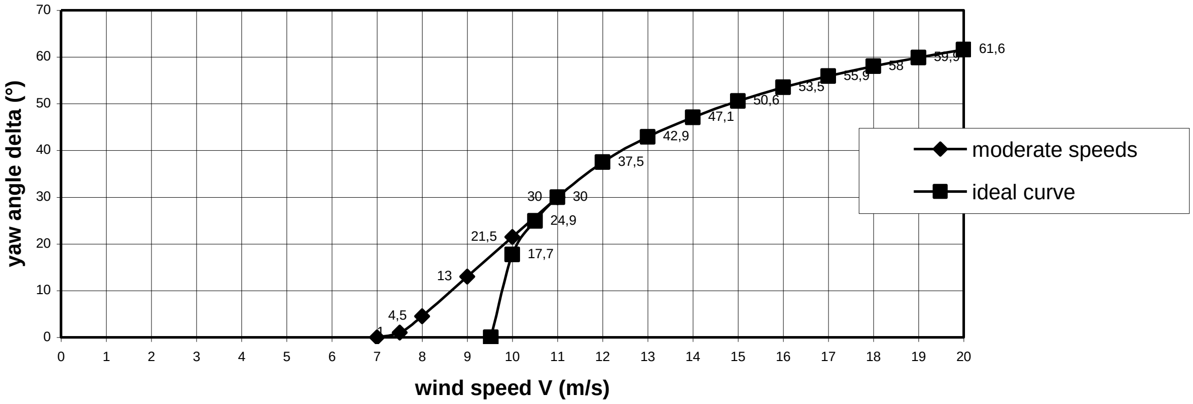

fig. 4 Estimated δ-V curve for a 12 mm meranti plywood vane blade

The P-n curves are used to check the matching with the $P_{mech}$-n curve of the generator for a certain gear ratio i (the VIRYA-5B3 has no gearing so i = 1). Because we are especially interested in the domain around the optimal cubic line and because the P-n curves for low values of λ appear to lie very close to each other, the P-n curves are not determined for low values of λ. The P-n curves are determined for wind the speeds 3, 4, 5, 6, 7, 8, 9, 10 and 11 m/s. At high wind speeds the rotor is turned out of the wind by a yaw angle δ and therefore the formulas for P and n are used which are given in chapter 7 of KD 35.

Substitution of R = 2.5 m in formula 7.1 of KD 35 gives:

$$n_\delta = 3.8197 * \lambda * \cos\delta * V \qquad \text{(rpm)} \qquad (8)$$

Substitution of ρ = 1.2 kg / $m^3$ and R = 2.5 m in formula 7.10 of KD 35 gives:

$$P_\delta = 11.781 * C_p * \cos^3\delta * V^3 \qquad \text{(W)} \qquad (9)$$

The P-n curves are determined for $C_p$ values belonging to λ is 3, 4, 5, 6, 7, 8, 9 and 9.6 (see figure 1). For a certain wind speed, for instance V = 3 m/s, related values of $C_p$ and λ are substituted in formula 8 and 9 and this gives the P-n curve for that wind speed. For the higher wind speeds the yaw angle as given by figure 4, is taken into account. The result of the calculations is given in table 2.

| | | V = 3 m/s δ = 0° | | V = 4 m/s δ = 0° | | V = 5 m/s δ = 0° | | V = 6 m/s δ = 0° | | V = 7 m/s δ = 0° | | V = 8 m/s δ = 4.5° | | V = 9 m/s δ = 13° | | V = 10 m/s δ = 21.5° | | V = 11 m/s δ = 30° | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| λ | $C_p$ | n (rpm) | P (W) | n (rpm) | P (W) | n (rpm) | P (W) | n (rpm) | P (W) | n (rpm) | P (W) | $n_\delta$ (rpm) | $P_\delta$ (W) | $n_\delta$ (rpm) | $P_\delta$ (W) | $n_\delta$ (rpm) | $P_\delta$ (W) | $n_\delta$ (rpm) | $P_\delta$ (W) |
| 3 | 0.13 | 34.4 | 41 | 45.8 | 98 | 57.3 | 191 | 68.8 | 331 | 80.2 | 525 | 91.4 | 777 | 100.5 | 1033 | 106.6 | 1234 | 109.2 | 1324 |
| 4 | 0.27 | 45.8 | 86 | 61.1 | 204 | 76.4 | 398 | 91.7 | 687 | 107.0 | 1091 | 121.9 | 1614 | 134.0 | 2145 | 142.2 | 2562 | 145.6 | 2750 |
| 5 | 0.39 | 57.3 | 124 | 76.4 | 294 | 95.5 | 574 | 114.6 | 992 | 133.7 | 1576 | 152.3 | 2331 | 167.5 | 3098 | 177.7 | 3701 | 181.9 | 3972 |
| 6 | 0.43 | 68.8 | 137 | 91.7 | 324 | 114.6 | 633 | 137.5 | 1094 | 160.4 | 1738 | 182.8 | 2570 | 201.0 | 3416 | 213.2 | 4080 | 218.3 | 4379 |
| 7 | 0.39 | 80.2 | 124 | 107.0 | 294 | 133.7 | 574 | 160.4 | 992 | 187.2 | 1576 | 213.2 | 2331 | 234.5 | 3098 | 248.8 | 3701 | 254.7 | 3972 |
| 8 | 0.28 | 91.7 | 89 | 122.2 | 211 | 152.8 | 412 | 183.3 | 713 | 213.9 | 1131 | 243.7 | 1673 | 268.0 | 2225 | 284.3 | 2657 | 291.1 | 2852 |
| 9 | 0.12 | 103.1 | 38 | 137.5 | 90 | 171.9 | 177 | 206.3 | 305 | 240.6 | 485 | 274.2 | 717 | 301.5 | 953 | 319.9 | 1139 | 327.5 | 1222 |
| 9.6 | 0 | 110.0 | 0 | 146.7 | 0 | 183.3 | 0 | 220.0 | 0 | 256.7 | 0 | 292.4 | 0 | 321.6 | 0 | 341.2 | 0 | 349.3 | 0 |

table 2 Calculated values of n and P as a function of λ and V for the VIRYA-5B3 rotor

The calculated values for n and P are plotted in figure 5. The optimum cubic line which can be drawn through the tops of the P-n curves, is also given in figure 5.

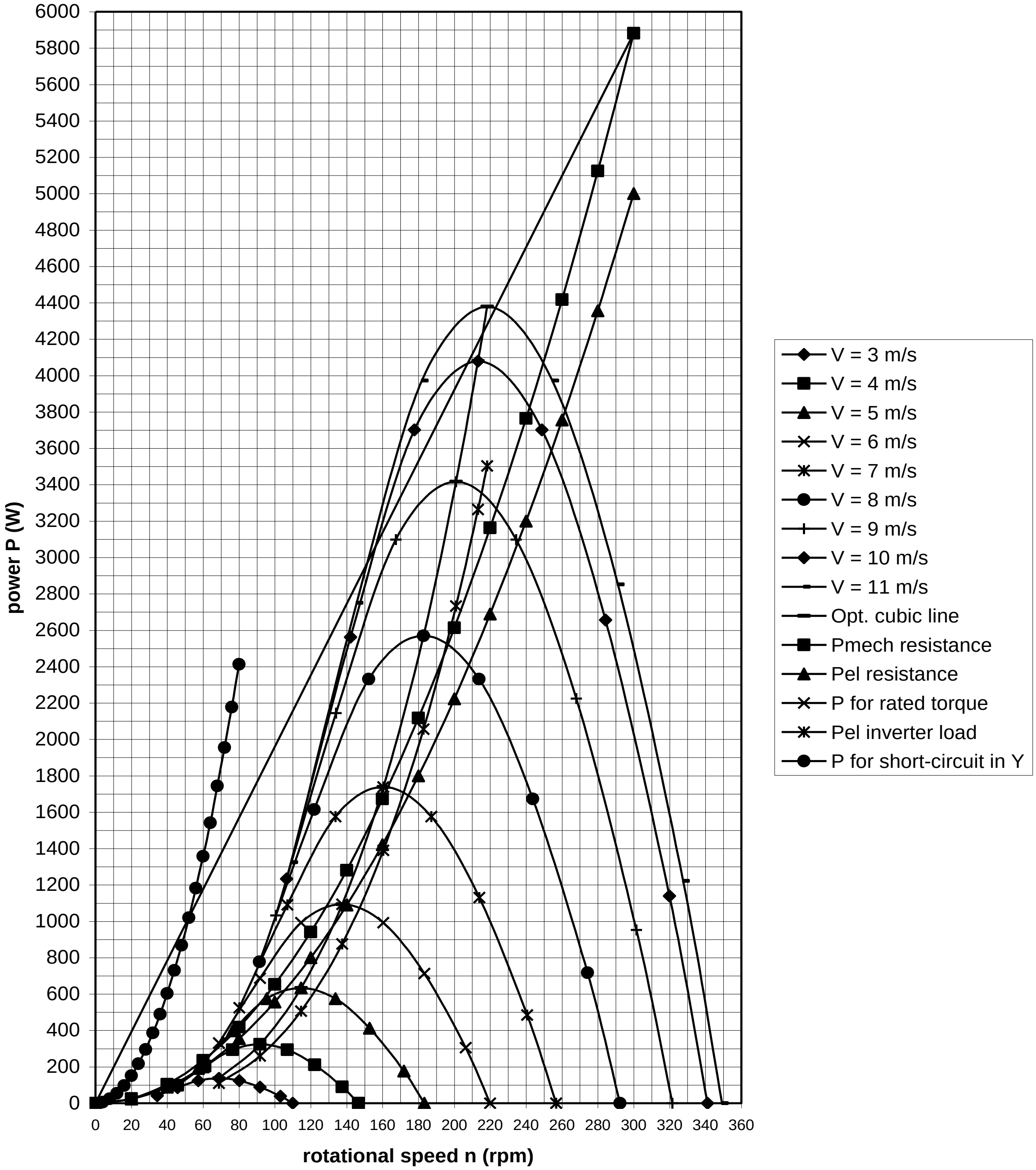

fig. 5 P-n curves of the VIRYA-5B3 rotor, optimum cubic line, $P_{mech}$-n and $P_{el}$-n curves for the generator with a resistance load such that $P_{el}$ = 5000 W at n = 300 rpm, P-n curve for the rated torque, $P_{el}$-n curve for an inverter load, P-n curve for short-circuit in star

## 6 Determination of the generator characteristics

An axial flux generator of Chinese manufacture has been chosen. Axial flux means that the magnetic flux which is flowing through the coils is in parallel to the generator axis. There is no iron in the coils and so the sticking torque is only determined by the friction of the bearings and the seal on the shaft. As there is no iron in the coils, there are no magnetic losses and the peak efficiency is rather high. Such generators are supplied by different Chinese suppliers like Hefei Top Grand, Xinda Green Energy, Hiestmotor and Qiangsheng Magnets. I have chosen Hefei Top Grand, website: www.china-topgrand.com because they gave the clearest answers on my questions. I have bought and tested a smaller generator type TGET165-0.15kW-500R at this company and they keep their promises. Measurements for this generator and experiments with a small wind turbine are given in report KD 595 (ref. 9).

For the VIRYA-5B3, I have chosen the generator with type TGET450-5KW-300R (450 refers to about the housing diameter, 5KW refers to the rated power in kW and 300R refers to the rated rotational speed in rpm). The generator can be bought at Hefei Top Grand but also at Alibaba. A data sheet about this generator can be found on the website of the supplier following the path: www.china-topgrand.com – product – Permanent Magnet Generator Outer Rotor – page 3 – TGET450-5kW-300R. The data sheet gives: Shape Drawing at point 4, Performance Parameter at point 5 and Curve Graph at point 6. At point 3, Range of Application, it is mentioned: “1 – 5 kW vertical axis wind turbine”. I think that this is mentioned because the generator has probably no oil seal on the rotor shaft. So no water will enter the bearings if the shaft is mounted vertical. The same was the case with the generator model TGET165-0.15kW-500R which I have tested. However, the housing of this generator was provided with a chamber in which an oil seal can be mounted. I expect that this is also the case for the TGET450-5kW-300R housing if it has no standard seal. The generator has a mass of 48 kg which seems acceptable for the VIRYA-5B3.

The generator is of the type “Outer Rotor” which means that the whole generator housing is rotating around the shaft. The rated loaded voltage at n = 300 rpm is specified as 220 VAC. So no DC voltage is specified but the loaded DC voltage can be calculated. This generator has a 3-phase winding with an internal star point and three phase wires are coming out of the hollow generator shaft. The given voltage is the voltage in between two of the three phases and not the phase voltage $U_f$, which is the voltage in between the star point and one of the phases. $U_f$ is a factor √ 3 lower, so 127.02 VAC. A large 3-phase rectifier (not included) must be used to get a DC current which is needed for the inverter. Rectification of a 3-phase current is explained in report KD 340 (ref. 3). However, it might be that the rectifier is included in the inverter and in this case the three phase wires are directly connected to the inverter. To stop the rotor, a 3-phase switch has to be mounted at the tower foot. The switch must be mounted as close as possible to the generator to prevent a voltage drop over the lines in between the generator and the switch.

The nominal line current I is specified as I = 13.1 A at n = 300 rpm. So the nominal power generated by one phase is $U_f * I = 127.02 * 13.1 = 1664$ W. So the nominal power generated by three phase is 3 * 1664 = 4992 W. This matches with the given power of 5 kW. The small difference must be caused by rounding off the current.

The sticking torque of the generator is very low without an oil seal and is only caused by the friction of the bearings. It is specified that this torque is less than 0.3 Nm. An oil seal is needed if the axis is horizontal. The sticking torque will be much higher if an oil seal is mounted but it is expected that it is low enough for the VIRYA-5B3 rotor (see calculation of the starting wind speed in chapter 4).

The generator has a shaft with a diameter of 59 mm and this shaft will certainly be strong enough for a horizontal axis wind turbine with a rotor diameter of 5 m. The generator housing has a collar with a diameter of about 150 mm at the front side and, I assume, ten, 20 mm deep threaded holes M12 at 36° and at a pitch circle of 130 mm (the threaded holes aren’t specified on the drawing given at point 4 of the data sheet so this has still to be verified).

The hub plate of the VIRYA-5B3 rotor must have a hole pattern which matches with that of the generator. The original head frame of the VIRYA-5 has a generator bracket which is in parallel to the generator shaft. The head frame of the VIRYA-5B3 must have a clamp in which the 59 mm shaft of the generator of Hefei Top Grand can be clamped such that the eccentricity e = 0.44 m and that the tilt angle in between the rotor shaft and the horizon is 5° .

The generator characteristics are given in point 6 of the data sheet. The $P_{el}$-n and the loaded U-n curves are given. The curves show measuring points but the measuring points aren't given in a table. The U-n curve is about a straight line through the origin and the $P_{el}$-n curve is about a parabola. This is an indication that the load is a fixed resistance for the whole range of measurements. I have performed this kind of measurements on a radial flux PM-generator made from an asynchronous motor. These measurements are given in chapter 7 and 9 of report KD 78 (ref. 10). These measurements show that the $P_{mech}$-n and $P_{el}$-n curves are about parabolas if the resistance isn't very low, that the U-n and Q-n curves are about straight lines through the origin and that the efficiency is about constant for a certain resistance. So these curves are estimated for the given generator of Hefei Top Grand from the given rated values at n = 300 rpm.

The given rated voltage is the alternating voltage $U_{AC}$ in between two of the three phases. For an inverter, the winding must be rectified. The rectified DC voltage $U_{DC}$ is a factor $0.955 * \sqrt{2} = 1.3506$ higher than $U_{AC}$ (if the voltage drop of the rectifier diodes is neglected). The unloaded or open voltage $U_{open}$ is also not specified. For a smaller generator type TGET320-1KW-350R, it has been found in chapter 3 of report KD 705 (ref. 11) that the ratio $U_{open}$ / $U_{DC}$ is about 68 / 56 = 1.2143. It is assumed that this ratio is also valid for the generator type TGET450-5KW-300R. So for the loaded DC voltage $U_{DC}$ at n = 300 rpm it is valid that $U_{DC}$ = 1.3506 * 220 = 297 VDC. For the open DC voltage $U_{open}$ at n = 300 rpm it is valid that $U_{open}$ = 1.2143 * 1.3506 * 220 = 361 VCD. The calculated values are given in the bottom line of table 3.

| n (rpm) | $U_{AC}$ (V) | $U_{DC}$ (V) | $U_{open}$ (V) | $P_{el}$ (W) | $\eta_{gen}$ (-) | $P_{mech}$ (W) | Q (Nm) | $P_{heat}$ (W) |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | - | 0 | 0 | 0 |
| 20 | 14.7 | 19.8 | 24.1 | 22.2 | 0.85 | 26.1 | 12.5 | 3.9 |
| 40 | 29.3 | 39.6 | 48.1 | 88.9 | 0.85 | 104.6 | 25.0 | 15.7 |
| 60 | 44.0 | 59.4 | 72.2 | 200.0 | 0.85 | 235.3 | 37.4 | 35.3 |
| 80 | 58.7 | 79.2 | 96.3 | 355.6 | 0.85 | 418.3 | 49.9 | 62.7 |
| 100 | 73.3 | 99.0 | 120.3 | 555.6 | 0.85 | 653.6 | 62.4 | 98.0 |
| 120 | 88.0 | 118.8 | 144.4 | 800.0 | 0.85 | 941.1 | 74.9 | 141.1 |
| 140 | 102.7 | 138.6 | 168.5 | 1088.9 | 0.85 | 1281.0 | 87.4 | 192.1 |
| 160 | 117.3 | 158.4 | 192.5 | 1422.2 | 0.85 | 1673.1 | 99.8 | 250.9 |
| 180 | 132.0 | 178.2 | 216.6 | 1800.0 | 0.85 | 2117.5 | 112.3 | 317.5 |
| 200 | 146.7 | 198.0 | 240.7 | 2222.2 | 0.85 | 2614.2 | 124.8 | 392.0 |
| 220 | 161.3 | 217.8 | 264.7 | 2688.9 | 0.85 | 3163.2 | 137.3 | 474.3 |
| 240 | 176.0 | 237.6 | 288.8 | 3200.0 | 0.85 | 3764.5 | 149.8 | 564.5 |
| 260 | 190.7 | 257.4 | 312.9 | 3755.6 | 0.85 | 4418.0 | 162.2 | 662.4 |
| 280 | 205.3 | 277.2 | 336.9 | 4355.6 | 0.85 | 5123.9 | 174.7 | 768.3 |
| 300 | 220 | 297 | 361 | 5000 | 0.85 | 5882 | 187.2 | 882 |

table 3 $U_{AC}$, $U_{DC}$, $U_{open}$, $P_{el}$, $\eta_{gen}$, $P_{mech}$, Q and $P_{heat}$ as a function of n

No rated torque Q is given for the generator. However, it is specified at point 5 of the data sheet that the generator efficiency $\eta_{gen}$ is at least 85 %. In figure 33 of KD 78 (ref. 10) it can be seen that the efficiency for a resistance load is about constant for every rotational speed and that it is high if the load resistance isn't low. It is easy to give the efficiency as a factor of 1 and it is assumed that $\eta_{gen}$ = 0.85 for all rotational speeds.

As the generator has no iron in the coils, the heat losses $P_{heat}$ are only caused by the copper losses in the winding. The $P_{mech}$-n, the $P_{heat}$-n and the Q-n curves of the generator can be derived by the formulas:

$$P_{mech} = P_{el} / \eta_{gen} \quad \text{(W)} \tag{10}$$

$$P_{heat} = P_{mech} - P_{el} \quad \text{(W)} \tag{11}$$

$$Q = 30\, P_{mech} / (\pi * n) \quad \text{(Nm)} \tag{12}$$

First the values of $P_{mech}$, $P_{heat}$ and Q are determined for n = 300 rpm. Substitution of $P_{el} = 5000$ W and $\eta_{gen} = 0.85$ in formula 10 gives that $P_{mech} = 5882$ W. Substitution of $P_{mech} = 5882$ and $P_{el} = 5000$ W in formula 11 gives that the heat loss $P_{heat} = 882$ W. Substitution of $P_{mech} = 5882$ W and n = 300 rpm in formula 12 gives that Q = 187.2 Nm. These values are also given in the bottom line of table 3.

The values for other rotational speeds are now calculated assuming that the U-n and Q-n curves are straight lines through the origin and that the P-n curves are parabolas. The wanted curves can now be derived from table 3. The $U_{AC}$-n, the $U_{DC}$-n and the $U_{open}$-n curves are given in figure 6.

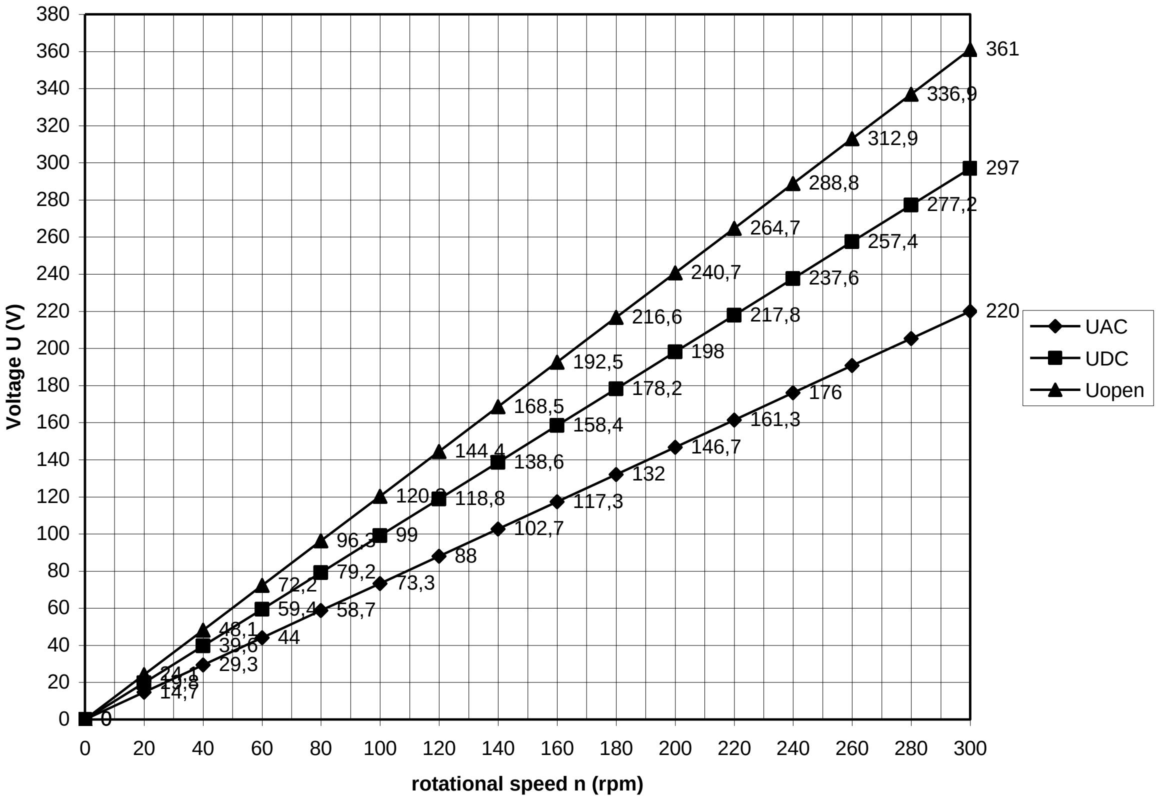

fig. 6 $U_{AC}$, $U_{DC}$ and $U_{open}$ as a function of n for a resistance load

The $P_{mech}$-n and the $P_{el}$-n curves for a resistance load are given in figure 5. In figure 5 it can be seen that the $P_{mech}$-n curve for a resistance load is intersecting with the optimum cubic line at a wind speed of about 7 m/s. For lower wind speeds, the $P_{mech}$-n curve is lying to the left side of the optimum cubic line and for higher wind speeds it is lying to the right side.

The Q-n curve is given in figure 7.

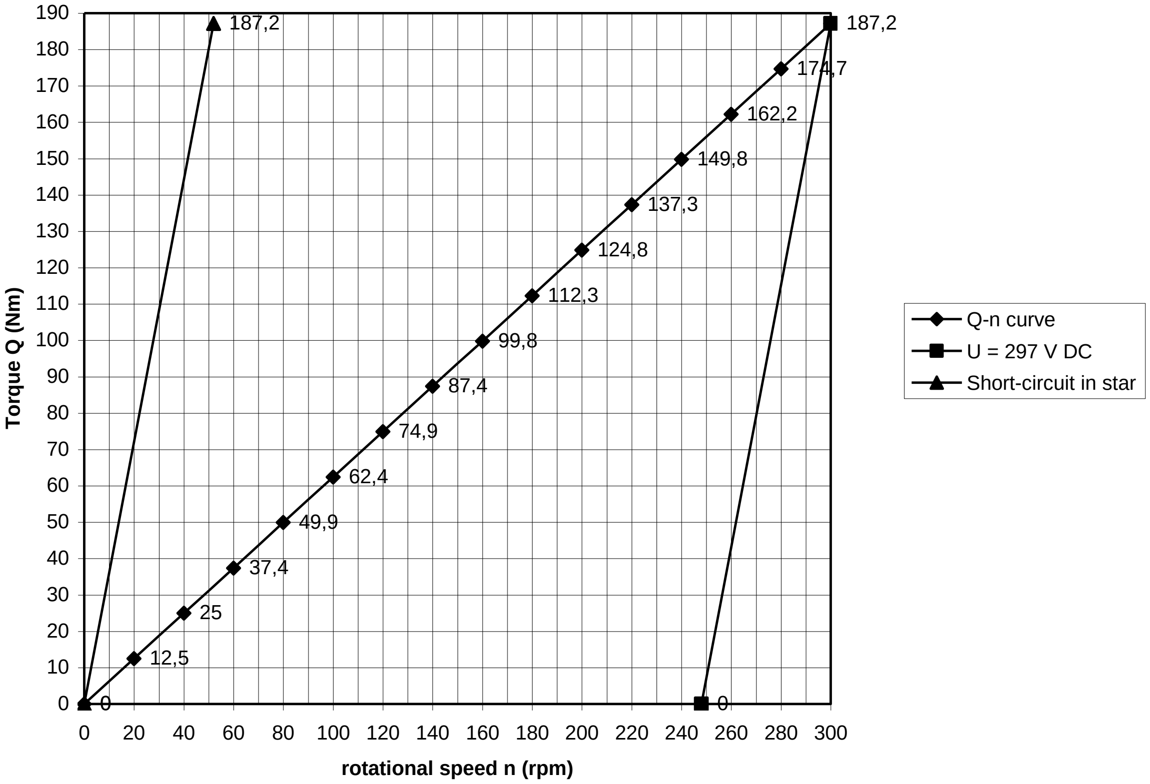

fig. 7 Loaded torque Q as a function of n for a resistance load, Q-n curves for 297 V DC and for short-circuit in star

So these figures are based on the manufactures specification for a resistance load at n = 300 rpm. The load resistance R can be calculated if it is assumed that three identical resistors are connected in star to the three phase wires. The voltage over one resistor is equal to the phase voltage $U_f$ = 127.02 V. The line current I = 13.1 A at n = 300 rpm. So according to the law of Ohm, the resistance R is given by R = U / I or R = 127.02 / 13.1 = 9.7 Ω.

If three resistors are used as load, the winding of one phase is used for all the time to generate power. This power varies according to a $\sin^2\alpha$ function. The power fluctuation is given in figure 2 of report KD 340 (ref. 3). If a 3-phase winding is rectified in star, only two of the three phases are generating power at the same time. This means that in one phase, power is only generated for $30° < \alpha < 150°$ and for $210 < \alpha < 330°$. This means that no power is generated for $0° < \alpha < 30°$, for $150° < \alpha < 210°$ and for $330° < \alpha < 360°$. The loss of generated power because of this effect is about 7 % of the power generated for a resistance load. But this effect is neglected and so it is assumed that the generator is able to generate a DC power of 5 kW at n = 300 rpm.

In the last column of table 3 it can be seen that the heat losses are maximal for n = 300 rpm. This is because the voltage and so also the current decrease at decreasing rotational speed. In figure 7 it can be seen that the torque for a resistance load decreases linear to the decrease of the rotational speed. A PM-generator can also have high torques at low rotational speeds so the chosen value of the resistance gives only a large torque for the rated rotational speed n = 300 rpm.

To know the real capacity of the generator, it should also be measured for lower values of the resistance at lower rotational speeds than 300 rpm up to at least the rated torque Q = 187.2 Nm which is valid for n = 300 rpm. As the current I is proportional to the torque Q, the copper losses and so $P_{heat}$, will then be the same for lower rotational speeds. The efficiency will be lower but this is acceptable.

A constant rated torque means that the power increases linear to the rotational speed. So a linear P-n curve “rated torque” through P = 0 W and n = 0 rpm and P = 5882 W and n = 300 rpm is also drawn in figure 5. Use of the generator below this line is acceptable without getting a too high value of $P_{heat}$. It can be seen that this line is intersecting with the optimum cubic line at about a wind speed of 9.5 m/s. The generator can supply a maximum torque which is even a lot higher than the rated torque. So the generator is certainly strong enough to load the rotor that strong that the optimum cubic line is followed. It is assumed that the inverter can be programmed such that the generator power is following the optimum cubic line.

The generator efficiency is 0.85 for a resistance load. In figure 5 it can be seen that for wind speeds below about 7 m/s, the load of the optimum cubic line is lower than the given resistance load. This means that the efficiency will be somewhat higher than 0.85. In figure 5 it can be seen that for wind speeds above about 7 m/s, the load of the optimum cubic line is higher than the given resistance load. This means that the efficiency will be somewhat lower than 0.85. However, the variation in efficiency is much smaller than for battery charging because the voltage is still increasing strongly at increasing rotational speed. So with only a small error, it is allowed to assume that the efficiency is constant and 0.85 for all working points of an inverter load. The real electrical power depends also on the losses in the rectifier and on the efficiency of the inverter. Rectifier losses are low for high voltages. Modern inverters have a very high efficiency. It is assumed that the total efficiency of generator, rectifier and inverter $\eta_{tot} = 0.8$. The $P_{el}$-n curve for an inverter load such that the optimum cubic line is followed and for a constant efficiency of 0.8 is also given in figure 5.

The working point for a certain wind speed is the point of intersection of the P-n curve of the rotor for that wind speed with the optimum cubic line. The electrical power for a certain wind speed is found by going down vertically from the working point until the $P_{el}$-n curve is crossed. The values of $P_{el}$ have been determined for every wind speed and are given in the $P_{el}$-V curve of figure 8. The maximum electrical power is about 3.5 kW at a wind speed of 11 m/s (or higher) which is very good for a windmill with a rotor diameter of 5 m.

If the generated energy is used to power a heat pump, about four times more heat is generated than the input electrical power. So even at moderate wind speeds, a substantial amount of heat will be generated by the VIRYA-5B3.

It is expected that the inverter needs a minimum input voltage to function. So the rotor must have a certain minimal rotational speed. This speed isn’t known but at the moment it is supposed that the voltage is too low for wind speeds below 3 m/s. This means that the little energy available in wind speeds below 3 m/s can’t be captured. So this is the reason why the $P_{el}$-V curve starts suddenly with $P_{el}$ = 110 W at V = 3 m/s. The critical voltage may lie lower and if this is the case, the $P_{el}$-V curve starts at a lower wind speed.

The $P_{el}$-V curve is valid for constant wind speeds and not for average wind speeds. The output for a certain average wind speed is larger than for a certain constant wind speed. This can be demonstrated as follows. Assume we have a constant wind speed of 5 m/s. In the $P_{el}$-V curve it can be read that $P_{el}$ = 506 W. Assume we have a wind speed of 7 m/s for one hour and of 3 m/s for one hour. So the average wind speed is 5 m/s. The power for V = 3 m/s is 110 W. The power for V = 7 m/s is 1390 W. So the average power is (110 + 1390) / 2 = 750 W. This is 244 W more or a factor 750 / 506 = 1.48 higher than for a constant wind speed of 5 m/s.

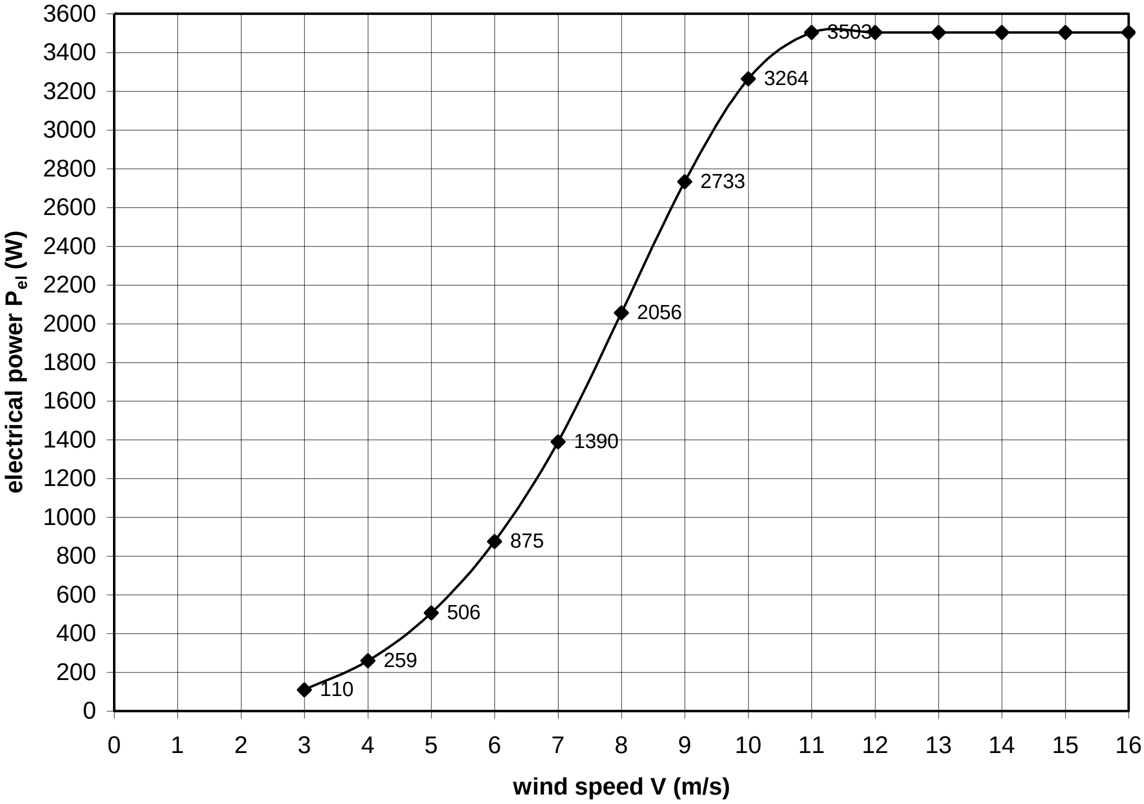

fig. 8 $P_{el}$-V curve for an inverter load such that the optimum cubic line is followed for wind speeds higher than 3 m/s

The $P_{mech}$-n, the $P_{el}$-n curves as given in figure 5 and the $P_{el}$-V as given in figure 8 are estimated and not measured. Measured characteristics are more accurate than estimated characteristics. So to be sure that an acceptable matching is realised for the chosen generator of Hefei Top Grand, it is necessary to buy one and to test it at a large test rig with which it is possible to also measure the torque Q. One should also select and buy an inverter and measure the real electrical output for grid connection.

It might be possible to use the rotor as a brake to stop the rotor. To verify if this is possible at any wind speed, one should know the P-n curve for short-circuit in star but this curve isn’t given. The PM-generator which is used for the measurements as given in KD 78 (ref. 10) was measured for different constant voltages rectified in star. The Q-n curves for 26 V star, 52 V star and 76 V star are given in figure 8 of chapter 4 of KD 78. The Q-n curve for short-circuit in star before the rectifier is given in figure 4 of chapter 3 of KD 78. If these curves are compared, it can be seen that all curves have about the same shape but that the curve is shifted to the right if the voltage is higher. All curves have about the same maximum value of about 29 Nm. The first part of each curve, up to about 2/3 of the peak value, so up to a torque of about 20 Nm, is about a straight line but the curves bend to the right for higher torques. The curves start at the rotational speed for which the open generator voltage is equal to the average charging voltage. This phenomenon is used to derive the wanted P-n curve for short-circuit in star for the VIRYA-5B3 generator.

In figure 6 it can be seen that the loaded DC voltage $U_{DC}$ = 297 V DC at n = 300 rpm. The unloaded open DC voltage $U_{open}$ = 361 V at n = 300 rpm. As the U-n curves are straight lines through the origin, it can be read that $U_{open}$ = 297 V DC at n = 248 rpm. This is 52 rpm lower than $n_{rated}$ = 300 rpm. Next it is assumed that Q-n line for a constant voltage of 297 V is a straight line in between the point Q = 0 Nm and n = 248 rpm and the point Q = 187.2 Nm and n = 300 rpm. This curve is also given in figure 7.

Short-circuit means a constant voltage U = 0 V. So the Q-n curve for short-circuit in star is found by moving the Q-n curve for 297 V DC that much to the left that it intersects with the origin. This means that it must go through the point Q = 0 Nm and n = 0 rpm and the point Q = 187.2 Nm and n = 52 rpm. This curve is also given in figure 7. Formula 12 can be written as:

$$P_{mech} = Q * \pi * n / 30 \qquad (W) \qquad (13)$$

To determine the P-n curve for short circuit in star, several points have to be chosen on the Q-n curve for short-circuit in star. This was done for every 4 rpm. P is then calculated for every point using formula 13. The result of this procedure is given in table 4. It is assumed that the Q-n curve is about straight for rotational speeds up to 80 rpm and the Q-n and P-n curves are extended up to this rotational speed. For higher rotational speeds than about 80 rpm, the Q-n curve for short-circuit in star will bend to the right and will have a maximum value at a certain rotational speed. This part of the curve can only be determined by measuring. So the P-n curve for short-circuit in star can't be determined for rotational speeds higher than about 80 rpm.

| n (rpm) | Q (Nm) | P (W) |
|---|---|---|
| 0 | 0 | 0 |
| 4 | 14.4 | 6.0 |
| 8 | 28.8 | 24.1 |
| 12 | 43.2 | 54.3 |
| 16 | 57.6 | 96.5 |
| 20 | 72 | 150.8 |
| 24 | 86.4 | 217.1 |
| 28 | 100.8 | 295.6 |
| 32 | 115.2 | 386.0 |
| 36 | 129.6 | 488.6 |
| 40 | 144 | 603.2 |
| 44 | 158.4 | 729.9 |
| 48 | 172.8 | 868.6 |
| 52 | 187.2 | 1019.4 |
| 56 | 201.6 | 1182.2 |
| 60 | 216.0 | 1357.2 |
| 64 | 230.4 | 1541.5 |
| 68 | 244.8 | 1743.2 |
| 72 | 259.2 | 1954.3 |
| 76 | 273.6 | 2177.5 |
| 80 | 288 | 2412.7 |

table 4 Calculated values of Q and P as a function of n for short-circuit in star

The P-n curve for short-circuit in star can now be derived from table 4 and is also given in figure 5. It can be seen that there is a large distance in between the P-n curve for short-circuit in star and the P-n curve of the rotor for V = 11 m/s. The P-n curve for short-circuit in star couldn't be determined for higher rotational speeds than 80 rpm but by interpolation it can be concluded that the generator can very well be used as a brake to stop the rotor at any wind speed.

Building of a prototype of the VIRYA-5B3 with the chosen PM-generator of Hefei Top Grand is only possible if the drawings are available but I won't make them. So only companies with enough engineering capacity should start with the VIRYA-5B3. The VIRYA-5B3 is certainly not a windmill which can be built by an amateur.

## 7 Use of the VIRYA-5B3 for 120 V battery charging

The VIRYA-5B3 with the generator type TGET450-5KW-300R is primary meant for grid connection. However, there are many places on earth where no grid is available and it would be nice if the VIRYA-5B3 could also be used to charge batteries. As the generator supplies a rather high DC voltage after rectification, the battery voltage must be rather high to get an acceptable matching at moderate wind speeds. After some research, it is found that a nominal battery voltage of 120 V is a good choice. It is assumed that 12 V lead acid batteries are used, so ten 12 V batteries (each minimal 100 Ah) have to be connected in series to get a nominal battery voltage of 120 V. Information about 12 V lead acid batteries is given in chapter 3 of report KD 378 (ref. 12).

The open voltage of a 12 V lead acid battery is about 12 V if the battery is 10 % full and about 12.6 V if the battery is 90 % full. The open voltage should be measured only after at least 15 minutes no charging or discharging. The loaded voltage of a 12 V battery depends on the charging state and on the current. The minimum loaded voltage is about 12.6 V for an almost empty battery at low currents. The maximum loaded voltage is normally limited up to 13.8 V to prevent gassing. So the average charging voltage of a 12 V battery is about 13.2 V. So the average charging voltage of a 120 V battery is about 132 V. The Q-n and the $P_{mech}$-n curves are now determined for a charging voltage of 132 V in the same way as it was done for short-circuit in star. It is checked if the matching is acceptable for this average charging voltage.

In figure 6 it can be seen that an open DC voltage of 132 V is obtained at a rotational speed of about 110 rpm. Figure 7 is now copied as figure 9 and the curve for short-circuit in star is replaced by the curve for 132 V DC. This means that the curve for 132 V DC is a straight line which is going through the point n = 110 rpm and Q = 0 Nm and the point n = 162 rpm and Q = 187.2 Nm.

To determine the $P_{mech}$-n curve for U = 132 V DC, several points have to be chosen on the Q-n curve for U = 132 V DC. This was done for every 4 rpm. $P_{mech}$ is then calculated for every point using formula 13. The result of this procedure is given in table 5. It is assumed that the Q-n curve is about straight for rotational speeds up to 186 rpm and the Q-n and P-n curves are extended up to this rotational speed. For higher rotational speeds than about 186 rpm, the Q-n curve for 132 V DC will bend to the right and will have a maximum value at a certain rotational speed. This part of the curve can only be determined by measuring. So the $P_{mech}$-n curve for 132 V DC can't be determined for rotational speeds higher than about 186 rpm.

Figure 5 is now copied as figure 10 but only the optimum cubic line, the curve "P for rated torque" and the curve "$P_{mech}$ resistance" are maintained. The $P_{mech}$-n curve for 132 V is added in figure 10. For the determination of the $P_{el}$-n curve for 132 V DC, it is necessary to estimate an efficiency curve. It is not allowed to take a constant efficiency as it was done for an inverter load as for a battery load, the voltage is almost constant and the power is only increasing by increase of the current. So the copper losses are increasing at increasing current, so at increasing rotational speed and this means that the generator efficiency $\eta_{gen}$ is decreasing at increasing rotational speed.

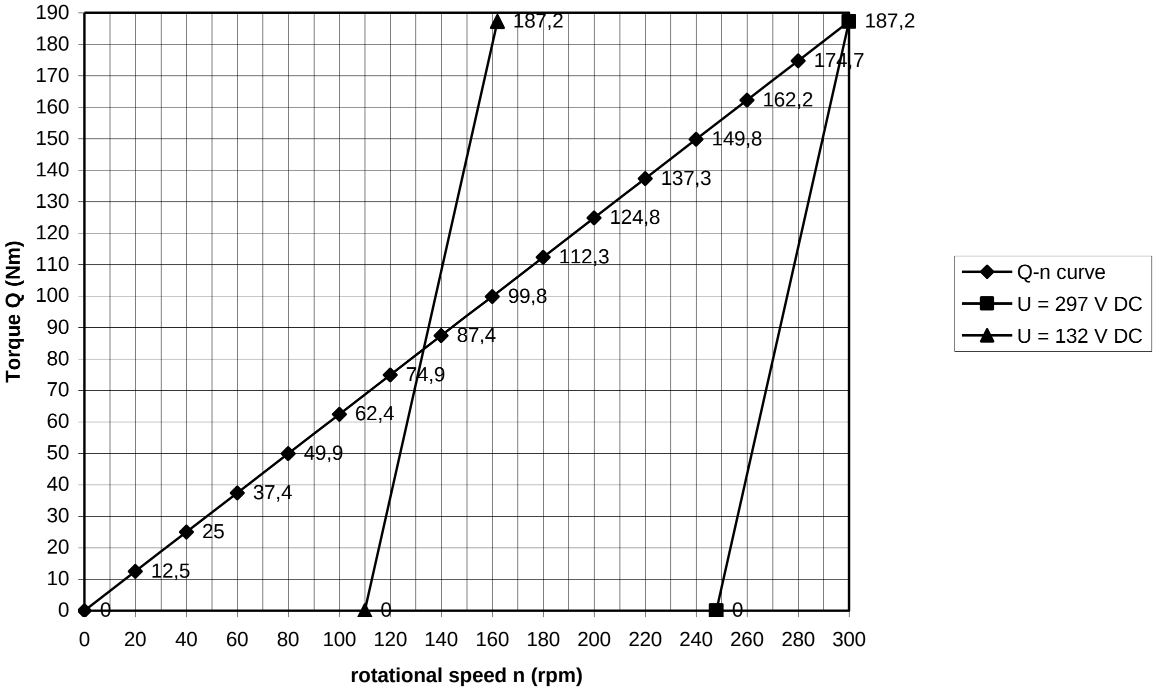

fig. 9 Loaded torque Q as a function of n for a resistance load, Q-n curves for 297 V DC and for 132 V DC

| n (rpm) | Q (Nm) | $P_{mech}$ (W) | $\eta_{gen}$ (-) | $P_{el}$ (W) | $P_{heat}$ (W) |
|---|---|---|---|---|---|
| 110 | 0 | 0 | 0 | 0 | 0 |
| 114 | 14.4 | 172 | 0.75 | 154 | 48 |
| 118 | 28.8 | 356 | 0.87 | 367 | 50 |
| 122 | 43.2 | 552 | 0.9 | 586 | 55 |
| 126 | 57.6 | 760 | 0.895 | 799 | 84 |
| 130 | 72 | 980 | 0.885 | 1014 | 122 |
| 134 | 86.4 | 1212 | 0.87 | 1228 | 182 |
| 138 | 100.8 | 1457 | 0.85 | 1436 | 255 |
| 142 | 115.2 | 1713 | 0.825 | 1632 | 343 |
| 146 | 129.6 | 1981 | 0.8 | 1824 | 446 |
| 150 | 144 | 2262 | 0.775 | 2010 | 565 |
| 154 | 158.4 | 2554 | 0.75 | 2189 | 690 |
| 158 | 172.8 | 2859 | 0.73 | 2378 | 829 |
| 162 | 187.2 | 3176 | 0.71 | 2561 | 985 |
| 166 | 201.6 | 3505 | 0.69 | 2739 | 1157 |
| 170 | 216.0 | 3845 | 0.67 | 2910 | 1327 |
| 174 | 230.4 | 4198 | 0.655 | 3197 | 1511 |
| 178 | 244.8 | 4563 | 0.64 | 3281 | 1711 |
| 182 | 259.2 | 4936 | 0.625 | 3461 | 1925 |
| 186 | 273.6 | 5329 | 0.61 | 3635 | 2185 |

table 5 Calculated values of Q and $P_{mech}$, $P_{el}$ and $P_{heat}$ as a function of n and $\eta_{gen}$ for 132 V DC

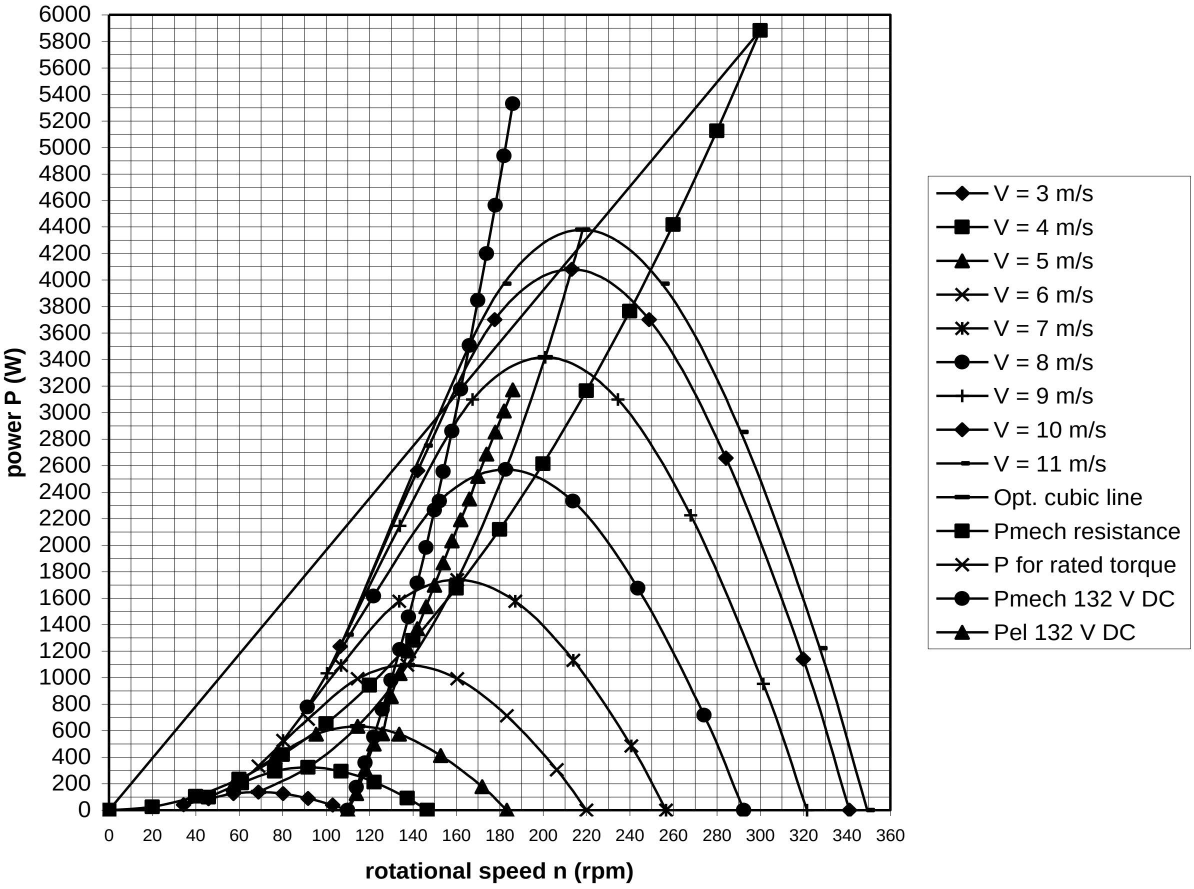

fig. 10 P-n curves of the VIRYA-5B3 rotor, optimum cubic line, $P_{mech}$-n curve for the generator with a resistance load such that $P_{el}$ = 5000 W at n = 300 rpm, P-n curve for the rated torque, $P_{mech}$-n and $P_{el}$-n curves for 132 V DC

It is assumed that the efficiency is 0.85 for the $P_{mech}$-n curve for a resistance load. In figure 10 it can be seen that the $P_{mech}$-n curve for 132 V DC is intersecting with the $P_{mech}$-n curve for a resistance load at about a rotational speed of 133 rpm. So it is assumed that the efficiency for 132 V DC is 0.85 for n = 133 rpm but also for n = 134 rpm. The efficiency is higher than 0.85 if the load is less than the resistance load and lower than 0.85 if the load is higher than the resistance load. It is assumed that the peak efficiency is 0.9 for n = 122 rpm. The estimated efficiency curve is given in figure 11. The values of $\eta_{gen}$ are taken from figure 11 and put in the fourth column of table 5. Next $P_{el}$ is calculated for the given values of $\eta_{gen}$. The $P_{el}$-n curve is then derived from table 5 and is given in figure 10. The dissipated heat $P_{heat}$ can be calculated using formula 11 and is given in the last column of table 5. The generated heat for a resistance load at n = 300 rpm is 882 W. So for about the same dissipated heat, the generator should not be driven faster than about 159 rpm for a 132 V DC load.

In figure 10 it can be seen that the $P_{mech}$-n curve for 132 V DC is intersecting with the optimum cubic line at a rotational speed of about 129 rpm. The wind speed which belongs to this point of intersection is about 5.7 m/s. So a wind speed of 5.7 m/s is called the design wind speed $V_d$. The point of intersection of the $P_{mech}$-n curve for 132 V DC is intersecting with the P-n curve of the rotor for a wind speed of 11 m/s at a rotational speed of about 165 rpm. So this is a bit higher than 159 rpm but this seems acceptable. The $P_{el}$-V curve for 132 V DC can be derived from figure 10 by going down from each working point until the $P_{el}$-n curve is crossed. The $P_{el}$-V curve is given in figure 12.

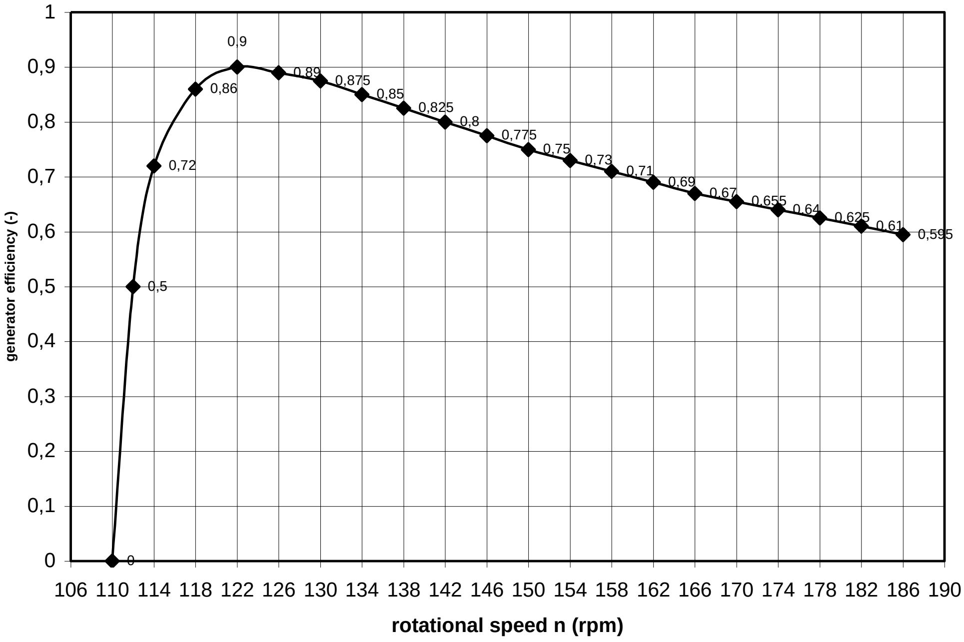

fig. 11 Estimated $\eta_{gen}$-n curve for 132 V DC for the generator type TGET450-5KW-300R

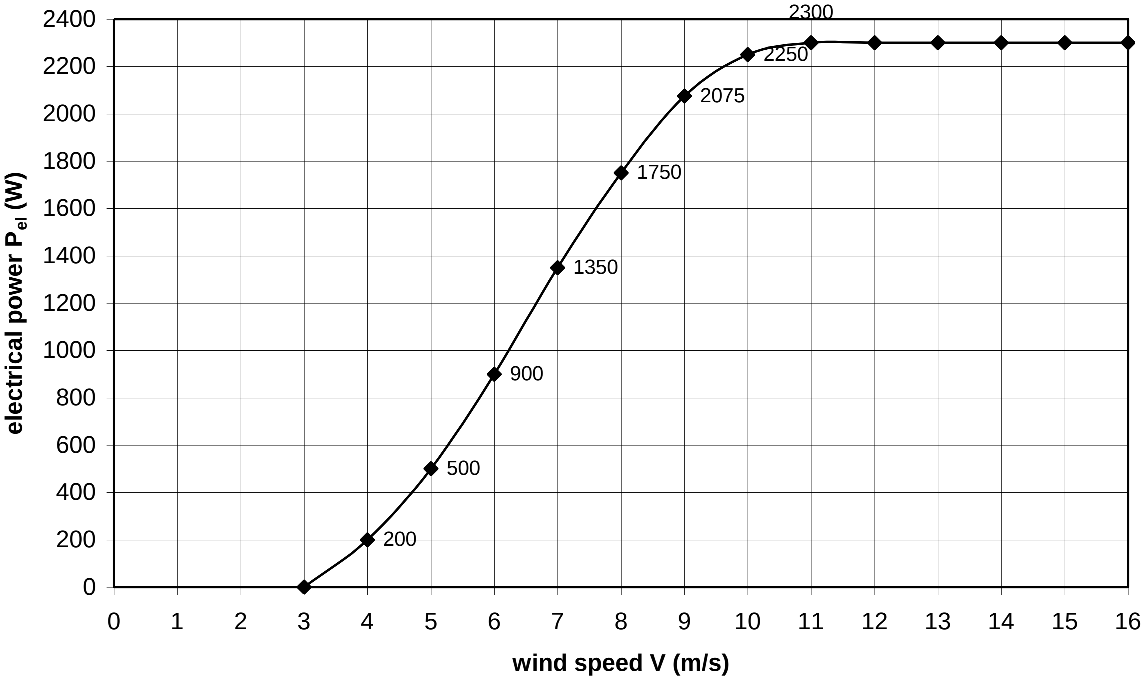

fig. 12 $P_{el}$-V curve for 132 V DC (120 V battery charging)

In figure 12 it can be seen that the cut in wind speed is 3 m/s and that the maximum power is 2300 W. This is much lower than for grid connection. This is caused by the lower generator efficiency at high powers and by the bad matching at V = 11 m/s. The mechanical power at V = 11 m/s is about 3500 W, so the dissipated heat is about 1100 W. This seems acceptable as this heat will be generated only shortly during strong wind gusts.

So the maximum power for 120 V battery charging is about 2400 W. The real charging voltage at this power is 138 V at this power if a battery charge controller is used. So the charging current is about 17.4 A which isn’t very high. A battery charge controller is needed to limit the maximum charging voltage up to 138 V or to 27.6 V for a set of two 12 V batteries connected in series. A 27.6 V, 200 W battery charge controller is described in a manual which can be found on my website at the bottom of the menu KD reports. The power can be increased up to 600 W by using a cooling plate size 750 * 500 mm with three transistor and six resistors on each plate. So five 600 W battery charge controllers connected in series can dissipate about 3000 W which is certainly enough. All five cooling plates and all five voltage controllers must be electrically isolated from each other! Another option is to design a new 138 V battery charge controller which can dissipate at least 2400 W but I can’t do that.

The rather high generator voltage has as advantage that rather thin wires can be used in between the windmill and the batteries. It is assumed that the rectifier and the short-circuit switch are mounted at the tower foot. So a cable with only two copper wires size 2.5 mm$^2$ seems enough to prevent large cable losses if the cables aren’t very long. For a large distance, one can use wire size 4 mm$^2$ or two 2.5 mm$^2$ wires in parallel.

The disadvantage of the high voltage is that it is dangerous. So the batteries must be placed in a closed room which is only accessible by qualified people. The battery voltage can be transferred into an AC voltage of 230 V and 50 Hz with an inverter. Selection of the correct inverter is out of the scope of this report.

## 8 Use of the VIRYA-5B3 for heating by a resistance load

It might be possible to use the VIRYA-5B3 for heating of a room by an electric heater. First it is assumed that this heater has the same resistance as the resistance which was used by the manufacturer to measure the generator. So this means that the $P_{mech}$-n and $P_{el}$-n curves are the same as the curves as given in figure 5.

The manufacturer has not specified how the resistors are connected. There are two possibilities, connection in star or connection in delta. In chapter 6 it was assumed that the resistors are connected in star, so in the same way as the generator winding. At page 13 it was calculated that each resistor has a resistance of 9.7 Ω. If the resistors are connected in delta, the voltage over one resistor is a factor √3 higher than for connection in star. So for the same power, the current must be a factor √3 lower. The power is given by $I^2 * R$ which means that $I^2$ must be a factor 3 lower. This means that the resistance R must be a factor 3 higher if the same power is dissipated at delta than at star. So each resistor must have a value of $3 * 9.7 = 29.1$ Ω if the three resistors are connected in delta. Connection in delta has as advantage that it is possible to connect one, two or three resistors to the generator. The dissipated power for one resistor is 1/3 of the power dissipated by three resistors. The dissipated power for two resistors is 2/3 of the power dissipated by three resistors.

First it is assumed that all three resistors are connected and so the $P_{mech}$-n and $P_{el}$-n curves as given in figure 5 are valid. In figure 5 it can be seen that the $P_{mech}$-n curve for a resistance load is about touching the P-n curve of the rotor for V = 5 m/s. This means that the generator is braking down the rotor till a very low rotational speed if the wind speed is lower than 5 m/s. So the rotor won’t start if the resistance is connected permanently to the generator. This problem can be solved by disconnecting all three resistors by a switch steered by the rotational speed or by the voltage but it is unacceptable that below a wind speed of 5 m/s, no stable power is produced.

Determination of the starting behaviour of the rotor at low wind speeds isn’t possible in the P-n graph because the P-values become low at low tip speed ratios. The starting behaviour can better be determined in the Q-n graph. The Q-n curves are determined in the same way as the P-n curves but one has to use the formula for Q in stead of P. The Q-n curves are only determined for the rather low wind speeds in between 3 m/s and 7 m/s.

The rotor is perpendicular to the wind for these wind speeds, so formula 4.3 out of KD 35 can be used. Substitution of $\rho = 1.2$ kg/m$^3$ and R = 2.5 m in this formula gives:

$$Q = 29.452 * C_q * V^2 \qquad \text{(Nm)} \qquad (14)$$

Formula 8 for $\delta = 0°$ changes into:

$$n = 3.8197 * \lambda * V \qquad \text{(rpm)} \qquad (15)$$

The result of the calculations is given in table 6.

| | | V = 3 m/s | | V = 4 m/s | | V = 5 m/s | | V = 6 m/s | | V = 7 m/s | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| λ | $C_q$ | n (rpm) | Q (Nm) | n (rpm) | Q (Nm) | n (rpm) | Q (Nm) | n (rpm) | Q (Nm) | n (rpm) | Q(Nm) |
| 0 | 0.0078 | 0 | 2.1 | 0 | 3.7 | 0 | 5.7 | 0 | 8.3 | 0 | 11.3 |
| 1 | 0.01 | 11.5 | 2.7 | 15.3 | 4.7 | 19.1 | 7.4 | 22.9 | 10.6 | 26.7 | 14.4 |
| 2 | 0.02 | 22.9 | 5.3 | 30.6 | 9.4 | 38.2 | 14.7 | 45.8 | 21.2 | 53.3 | 28.9 |
| 3 | 0.0433 | 34.4 | 11.5 | 45.8 | 20.4 | 57.3 | 31.9 | 68.8 | 45.9 | 80.0 | 62.5 |
| 4 | 0.0675 | 45.8 | 17.9 | 61.1 | 31.8 | 76.4 | 49.7 | 91.7 | 71.6 | 106.7 | 97.4 |
| 5 | 0.078 | 57.3 | 20.7 | 76.4 | 36.8 | 95.5 | 57.4 | 114.6 | 82.7 | 133.3 | 112.6 |
| 6 | 0.0717 | 68.8 | 19.0 | 91.7 | 33.8 | 114.6 | 52.8 | 137.5 | 76.0 | 160.0 | 103.5 |
| 7 | 0.0557 | 80.2 | 14.8 | 107.0 | 26.2 | 133.7 | 41.0 | 160.4 | 59.1 | 186.7 | 80.4 |
| 8 | 0.035 | 91.7 | 9.3 | 122.2 | 16.5 | 152.8 | 25.8 | 183.3 | 37.1 | 213.3 | 50.5 |
| 9 | 0.0133 | 103.1 | 3.5 | 137.5 | 6.3 | 171.9 | 9.8 | 206.3 | 14.1 | 240.0 | 19.2 |
| 9.6 | 0 | 110.0 | 0 | 146.7 | 0 | 183.3 | 0 | 220.0 | 0 | 256.0 | 0 |

table 6 Calculated values of n and Q as a function of λ and V for the VIRYA-5B3 rotor

The Q-n curves for different wind speeds are given in figure 13. The optimum parabola (the curve through the points for λ = 6) is also given in figure 13.

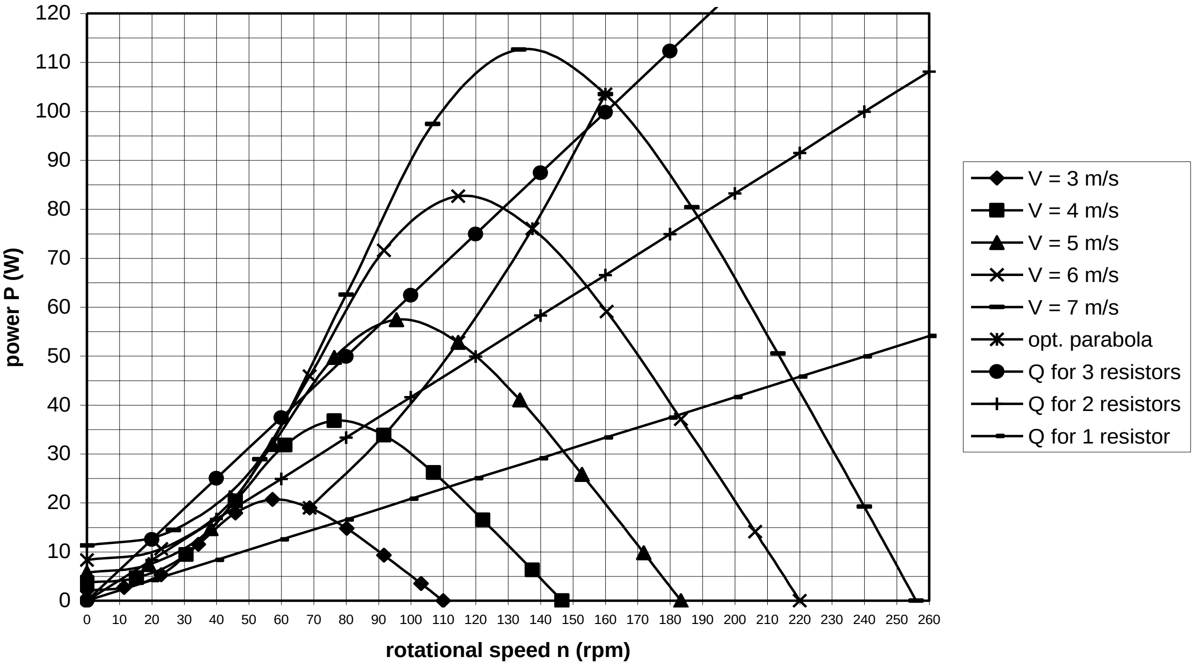

fig. 13 Q-n curves and optimum parabola. Q-n curves generator for three resistance loads

The Q-n curve for a resistance load for three resistors of 29.1 Ω connected in delta can be derived directly from table 3. The Q values are copied for values of n from n = 0 rpm up to n = 260 rpm. This curve is labelled in figure 13 as “Q for 3 resistors”. In table 3 it is given that Q = 0 Nm for n = 0 rpm. This isn’t true as the generator has a small friction torque but this friction torque is neglected.

The torque for two resistors can be found by taking 2/3 of the value for three resistors. This curve is labelled in figure 13 as “Q for 2 resistors”. The torque for one resistors can be found by taking 1/3 of the value for three resistors. This curve is labelled in figure 13 as “Q for 1 resistor”.

In figure 13 it can be seen that the curve “Q for 3 resistors” is about touching the Q-n curve of the rotor for V = 5 m/s at a rotational speed of about 80 rpm. So if the rotor is turning, it will stop if the wind speed becomes lower than 5 m/s. However, in figure 13 it can also be seen that there are three points of intersection of the curve “Q for 3 resistors” with the Q-n curve of the rotor for V = 7 m/s. These points are lying at rotational speeds of 21 rpm, 63 rpm and 163 rpm. So in between 21 rpm and 63 rpm the curve “Q for 3 resistors is lying higher than the Q-n curve of the rotor for V = 7 m/s. This means that the rotor will only reach the rotational speed of 21 rpm and that it won’t even start at a wind speed of 7 m/s! This is certainly not acceptable.

In figure 13 it can be seen that the curve “Q for 1 resistor” is about touching the Q-n curve of the rotor for V = 3 m/s at a rotational speed of about 15 rpm. So the rotor will start at this wind speed and so one resistor can be connected permanently. The curve “Q for 1 resistor” is intersecting with the Q-n curve of the rotor at a rotational speed of about 77 rpm so this will be the rotational speed at a wind speed of 3 m/s.

Next assume that the wind speed is increasing slowly up to 4 m/s. This means that the curve “Q for 1 resistor” is followed to the right until the point of intersection with the Q-n curve of the rotor for V = 4 /s. This point lies at a rotational speed of about 111 rpm. Assume that resistor 2 is connected at this rotational speed. This means that the Q-n curve of the rotor for V = 4 m/s is followed to the left until the point of intersection with the curve “Q for 2 resistors” which lies at a rotational speed of about 86 rpm.

Next assume that the wind speed is increasing slowly up to 5 m/s. This means that the curve “Q for 2 resistor is followed to the right until the point of intersection with the Q-n curve of the rotor for V = 5 /s. This point lies at a rotational speed of about 120 rpm. Assume that resistor 3 is connected at this rotational speed. This means that the Q-n curve of the rotor for V = 5 m/s is followed to the left until the point of intersection with the curve “Q for 3 resistors” which lies at a rotational speed of about 92 rpm.

So now all three resistors are connected. If the wind speed is still increasing, now the $P_{mech}$-n curve as given in figure 5 is followed to the right. This curve is intersecting with the optimum cubic line at a rotational speed of about 154 rpm belonging to a wind speed of about 6.8 m/s. So the matching is perfect for this wind speed but it is acceptable for wind speeds in between 5 m/s and 10 m/s.

If the wind speed is high but slowly decreasing, first resistor 3 has to be disconnected. This can be done at a rotational speed of about 80 rpm. If the wind speed is still decreasing, resistor 2 has to be disconnected. This can be done at a rotational speed of about 70 rpm.

So it can be concluded that the VIRYA-5B3 can be used for heating of a room if three 29.1 Ω resistors are used in delta and if two of these resistors are connected and disconnected at the right rotational speed of the rotor. One must be aware that by using the generated power for direct heating one gets only the same heat power as the supplied electrical power. Using a heat pump generates about a factor four more heat than the supplied electrical power. However, using a heat pump means that the wind turbine must be connected to the grid by a 3-phase inverter and that a heat pump and floor heating are required. Preparing of the floor with heat pipes is a lot of work for an existing house. The whole installation of an inverter, a heat pump and floor heating is much more expensive than only an electrical heater.

The electrical power output of the generator at low wind speeds is higher than the electrical power output of the inverter load as there are no rectifier and inverter losses but it is lower because the matching isn’t optimal. To get an impression one can use the $P_{el}$-V curve as given in figure 8. For high wind speeds, the matching for the $P_{mech}$-n curve of a resistance load is not as good as for the optimum cubic line which can be followed by an inverter. So the power at high wind speeds will be somewhat lower than for an inverter load.

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